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Published in:
Proceedings of the 25th International Conference on Plastic Optical Fibers 2016

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

3D-printed PMMA Preform for Hollow-core POF Drawing

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Abstract: In this paper we report the first, to our knowledge, 3D-printed hollow-core poly(methyl methacrylate) (PMMA) preform for polymer optical fibre drawing. It was printed of commercial PMMA by means of fused deposition modelling technique. The preform was drawn to cane, proving good enough quality of drawing process and the PMMA molecular weight to be appropriate for drawing. This ascertains that the manufacturing process provides preforms suitable for hollow-core fibre drawing. The paper focuses on maximisation of transparency of PMMA 3D printouts by optimising printing process parameters: nozzle temperature, printing speed and infill.

1. Introduction

3D printing, or additive-layer manufacturing (ALM), is a group of techniques that have recently been revolutionising the field of manufacturing [1, 2]. They are widely considered the manufacturing technologies of the future. It is due, among other things, to ever lower price and hence wider accessibility, ease of customisability, ability to reproduce complex shapes, as well as growing number of available materials and capabilities stemming from them.

The particular ALM technique used in this paper is fused deposition modelling (FDM). It is the most popular ALM technique, and it seems especially well suited to use in manufacturing polymer optical fibre (POF) preforms. Firstly, FDM relies on printing with polymers that are thermoplastic, which is also the key material requirement for preform fabrication. Moreover, this technique can be capable of creating preforms that would be extremely difficult to make in another way, e.g. having non-circular holes. Finally, FDM offers the highest ability of all ALM techniques to mix various materials within one printout. This opens up the possibility of tuning wide range of material properties with unprecedented ease (chemical composition, refractive index, transparency, coefficient of thermal expansion, flexibility, affinity to water, biodegradability, etc.).

Hollow-core (HC) microstructured optical fibres are drawing increasing attention as they can offer better transmission at those wavelengths where material loss is high. Air-guidance is of particular interest for microstructured polymer optical fibres (mPOF), in which attenuation is generally an issue. Especially given the problem of high transmission losses reported for optical fibres drawn from a 3D-printed solid-core polymer preform [3]. Moreover, the effects of other material properties such as non-linearity can be reduced if a HC is used [4]. For example, within some regions of the infrared Argyros et al. [5] demonstrated loss much lower than the respective material loss for a HC mPOF made of poly(methyl methacrylate) (PMMA). In this work we have chosen to 3D print a HC mPOF preform with a structure similar to the one proposed by Pryamikov et al. [6] in silica fibres, where the guidance was not based the photonic band gap principle or Kagome lattice claddings, but relied on the negative curvature of the core wall and the scattering characteristics of the cladding elements. As a proof of concept, this type of structure is supposed to be relatively easier to 3D print from the viewpoint of printing resolution than typical HC mPOF preforms having several tens of tiny holes. A thick HC fibre with negative curvature has been 3D printed by Cruz et al. for terahertz applications [7]. The possibility of producing HC mPOF preforms that are drawable can make the range of possible applications much wider.

The FDM technique has already been used by Cook et al. [3] to 3D-print a solid-core preform of styrene-butadiene copolymer and polystyrene. The authors managed to draw fibre from the preform, but a high loss value excluded any practical applications. In this paper we report the first, to our knowledge, 3D printed hollow-core preform for POF drawing. The reason behind the use of a HC structure is to reduce importance of material transparency, as the highest light density corresponds to the air region of the core. The preform was printed of PMMA, which has been proven to display good transparency, and which is the best-studied material for POF drawing. Choice of design and fabrication procedure are described, paying special attention to transparency optimisation during 3D printing stage. We show that the HC PMMA mPOF preform is drawable to a cane, an intermediate step between preform and fibre. This suggests that a HC mPOF may be obtained by using the proposed method. The results of drawing the preform to cane are presented and discussed in order to identify potential points of improvement.

2. Design and fabrication

2.1 Design

The preform was designed as an enlarged version of the structure of the silica HC microstructured optical fibre investigated by Pryamikov et al. [6]. The structure to 3D print basically consisted of eight capillary tubes inserted into an outer hollow tube, as shown in Figure 1. In the fibre manufactured in [6], the relative preform was made by capillary stacking and the capillaries were fused together by using an oxygen-hydrogen burner. The CAD design was carried out by using SolidWorks 2015. The external and internal diameters of the outer tube were 65.0 and 45.6 mm, respectively. The length of the preform was 102.5 mm. The eight tubes inside the larger tube had the same external and internal diameter, i.e. 12.6 mm and 9.6 mm, respectively. The resulting air core diameter of the preform was 20.4 mm.

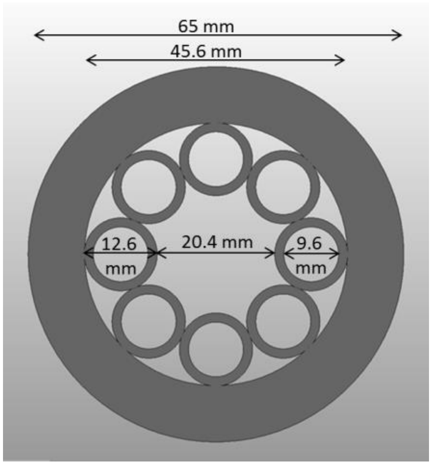

Figure 1. Cross section view of the preform to 3D print.

2.2 3D printing

The main focus of the optimisation of 3D printing parameters was transparency increase. Despite all the advantages of the FDM technique introduced above, it is intrinsically not well-suited for manufacturing transparent printouts, as opposed to some other competing AML techniques. In FDM, a printout layer is created by melting together threads of plastic filament, normally leaving air voids between them, which leads to creating sources of light scattering. Transparency optimisation of FDM-printed structures relied then on assuring that adjacent threads melt together as much as possible, leaving no air voids in the printout.

All printouts described in this paper were printed from a commercially-available PMMA filament, dried at 85 °C for drawing. The machine was an UP! 3D printer, working with the dedicated UP! slicer (software which transforms a 3D model into a series of printer commands) with the FixUp3D extension.

Transparency optimisation experiments were performed on 4 mm thick slices of the preform. After printing, the samples were polished from top, bottom and the side, which allowed for qualitative assessment of transparency.

The following parameters were varied during optimisation process:

- Nozzle temperature
- Printing speed (speed of nozzle movement)
- Infill

All these parameters are machine- and filament-dependent, so the optimised values should be treated as an indication only. Moreover, the software uses a non-standard parameter set for infill, which is not easily comparable with those of other slicers. For these reasons, qualitative discussion of optimisation process is presented below, and quantitative data are provided where possible.

Nozzle temperature values from 250 °C to 300 °C with 10 °C step were tested to find that the optimal temperature values from the viewpoint of transparency were 280-290 °C. For the temperatures below 280 °C filament threads seemed not to melt together well, whereas for 300 °C viscosity was probably too low. The nozzle temperature used for fabricating the final preform was decided to be 290 °C.

Printing speed, which is the speed at which the nozzle moves, was varied from 40 mm/s down. The general rule was found to be that the lower the speed, the better the transparency. Practical constraints are the only limiting factor keeping the speed high, as lowering the printing speed increases overall manufacturing time. Transparency improvement at low printing speed seems to be linked to heat transfer from the nozzle to the sample. If printing speed is low, the areas adjacent to the thread being deposited have more time to heat up. This results in the adjacent threads melting together better, minimising formation of air voids. The speed at which the final preform was printed was decided to be 5 mm/s.

The need for optimal infill (or filament feed rate) was identified, while too high and too low values were resulting in transparency decrease. When infill was too low, there was not enough material deposited by the nozzle to fill all required volume of printout. Too high infill values were making excessive material aggregate at printout walls, deteriorating print precision and hindering operation of the printer. In this case, air voids at thread junctions were also found bigger.

Apart from the optimised parameters described above, there were two parameters that were kept constant throughout the tests: layer thickness and printing bed temperature. The former was set to 150 µm, which was the lowest value recommended for the 3D printer, and any lower value would result in tremendous increase in preform fabrication time. On the other hand, higher layer thickness would decrease lateral (XY) resolution of printout. Regarding printing bed temperature, it was kept at around 105 °C (the highest settable value for the machine). As it has already been mentioned, the higher the temperature of the adjacent threads, the better they melt together. However, the favourable influence of the printing bed temperature was only visible until around 2 cm up from the printing bed, while at higher distances the heat coming from the printing bed was being dissipated.

The final preform was printed in 9 days, 16 hours and 43 min (232.7 h), consuming 226.8 g of the material (Figure 2). The printing time was much longer than this reported by Cook et al. [3] (6 h) to provide highest practically achievable transparency of the preform.

Figure 2. Hollow-core PMMA mPOF preform on the printing bed.

2.3 Post-print processing

The preform was dried for two days at 85 °C, after which it was machined in order to reduce surface roughness resulting from the 3D printing process. The final diameter (i.e. diameter of the outer tube) and length of the preform were 60.0 mm and 100.0 mm, respectively, giving an aspect ratio of 0.6. The preform was then dried at 80 °C for six days before drawing.

2.4 Drawing to cane

The drawing conditions were unknown for the particular PMMA grade the preform was made of. In particular, important parameters such as the molecular weight, which gives information about the average chain length of the polymer, were not available. The optimal molecular weight for drawing PMMA is around 60000 g/mol [4]. Also considering the specific HC structure, we decided to start from a low temperature (around 50 °C below the usual temperature for commercial PMMA rods, which is around 190 °C) and increase it gradually to find the minimum temperature suitable for drawing. The final drawing temperature was 10 °C below the usual drawing temperature for PMMA. We conducted the process at high tension aiming to decrease surface roughness. High tension can indeed yield lower roughness and therefore help reduce fibre loss [8]. Several canes were obtained from the HC mPOF preform, as shown in Figure 3.

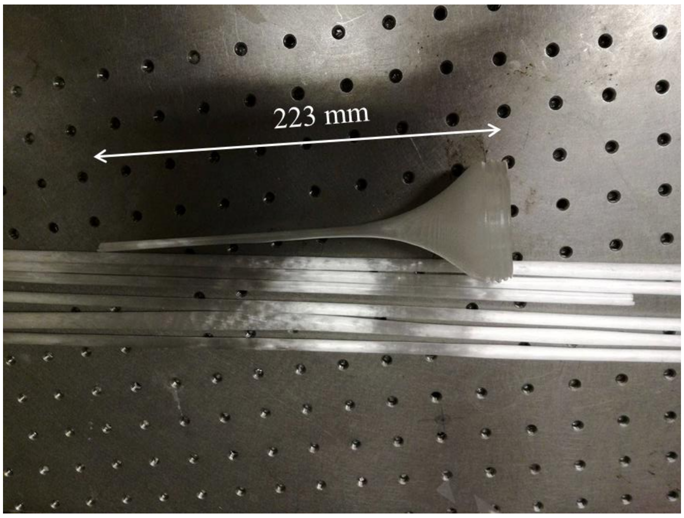

Figure 3. Hollow-core PMMA mPOF canes obtained from 3D printed preform drawing.

Figure 4 displays the cross-section of one of the HC PMMA mPOF canes, whereas the geometrical parameters are reported in Table 1. In Figure 4 it may be seen that the drawing led to two phenomena. First, some capillaries moved away from each other. This may be a consequence of the very thin layer of material keeping them joined. Furthermore, even a small inhomogeneity in heat distribution within the preform can strongly affect the fluid mechanical response of the HC structure and break its initial symmetry. The second phenomenon we observed is the holes becoming elliptical. As a result, relative to the outer diameter of the cane, the air core diameter was larger than at the preform stage (2.2 mm/4.7 mm=47% instead of 20.4 mm/60.0 mm=34%). Also, the walls of the capillaries were thicker than those in the preform. Such deviations from the initial design can be reduced by improving the drawing conditions for these particular types of HC structure and PMMA.

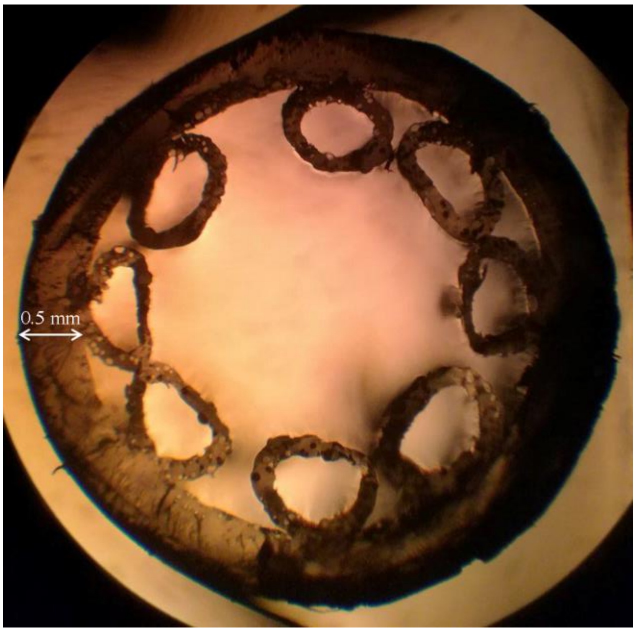

Figure 4. Cross-section of a HC PMMA mPOF cane.

Wall thickness of the capillaries	0.16 mm
Wall thickness of the outer tube	0.5 mm
Diameter of the air core	2.2 mm
Major diameter of elliptical holes	0.6 mm
Minor diameter of elliptical holes	0.4 mm
External diameter of the cane	4.7 mm

Table 1. Average geometrical parameters for a HC PMMA mPOF cane.

3. Conclusions and outlook

To the best of our knowledge, this paper presented the first 3D-printed hollow-core preform for POF drawing. It was made of PMMA, which is the most popular and hence best-studied material for preform fabrication. It is expected that, thanks to this, further drawing optimisation process should be relatively quick and straightforward, leading to favourable mechanical and optical preform properties. The preform was proven to be drawable, which implies that the optimised procedure should be suitable for producing hollow-core POF.

In the next step, the cane presented in the paper will be drawn to fibre and light guidance will be checked. Further changes to the fabrication procedure will encompass improvement of drawing conditions (to avoid separation of capillaries), as well as performing high-temperature annealing before drawing. Furthermore, a new design will be proposed, as the current one was originally developed for silica [6].

3. Acknowledgement

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n° 608382.

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